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Sizing and simulation of a photovoltaic-wind energy system using batteries, applied for a small rural property located in the south of Brazil

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ABSTRACT

This paper presents a methodology for sizing and simulating an autonomous photovoltaic-wind hybrid energy system with battery storage, using simulation tools and linear programming. The developed model is useful for energizing remote rural areas and produces a system with minimum cost and high reliability, based on the concept of loss of power supply probability (LPSP), applied for consecutive hours. To calculate the solar power and the wind power, a statistical model based on Beta and Weibull probability density functions, respectively, is used. Some scenarios are calculated and compared, using different numbers of consecutive hours and different LPSP values. As a result, a complete sizing of the system and a long-term cost evaluation are presented.

Contents

1. Introduction

The current interest in the control and use of renewable energy sources is mainly due to the constant progress that these technologies are presenting, and the great need for energy in remote rural areas of the developing countries, where, usually, the only available energy resources are renewable.

Although the use of natural resources, such as wind power and solar power, seems really obvious in Brazil, it has been neglected due to a lack of reliable information, insufficient infrastructure, higher costs (when compared with the hydroelectric source), and unclear regulations about management,and technical, and legal issues [1,2]. Despite these problems, some systems have been installed to meet people's needs in more isolated locations.

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In 2003, a hybrid wind-photovoltaic diesel was developed in the municipality of Maracanã, state of Pará, Brazil. The main objectives were to supply electricity to an isolated community typical of the Amazon region, to reduce the use of fossil fuel (diesel), to increase the energy diversification, to make a socioeconomic study of the population involved, and to evaluate the model for the implementation of similar systems in other places of the country [3].

Renewable energy resources, such as solar and wind, are vast, and unlike fossil fuels, they are very well distributed all over the world. The main problem associated with them is their diluted nature and the consequent need for high cost equipment to convert them into usable forms. In spite of the energy resources being free, their extraction is not. Economic considerations, quality, and the type of necessary energy to fulfill the final consumer needs have an important role in the development and selection of the technology. The numbers regarding the energy cost, based on the use of different technologies, are always subject to fluctuations, depending on the technological advances. Recent technological tendencies are very encouraging for renewable technologies.

Much work has been done to calculate the sizing of photovoltaic-wind energy system. Optimization models, using linear programming, are proposed in [4–6]. Probabilistic calculations, involving the loss of power supply probability (LPSP) as a measure of reliability, are used for the optimal sizing of energy systems with battery banks. The LPSP is the probability that an insufficient power supply results when the hybrid system (PV, wind power, and energy storage) is not able to satisfy the load demand [7–10]. Methods for sizing hybrid energy systems (photovoltaic/wind), with emphasis on the cost and/or performance of the system, are presented in [11–14]. A method to optimize the configurations of the hybrid system, based on a genetic algorithm, is presented in [15]. Several software programs are available for sizing hybrid systems, such as HOMER and HYBRIDS. HOMER has been very much used in renewable energy system case studies [16,17], and in system validation tests [18]. However, the program's limitation is that the algorithms and calculations are not accessible. HYBRIDS can make simulations, but is not designed to get an optimized configuration [19]. Other works have presented optimization techniques for hybrid solar–wind system, such as graphic construction methods, artificial intelligence methods, iterative technique, and multiobjective design [20,21].

The solar radiation and wind speed data, as well as their statistical treatment, are necessary for the correct sizing of the energy system, and have also been the object of several studies. Methods such as synthetic generation of data, extrapolation, stochastic simulation, and distribution models are presented in [22–25].

This paper presents a methodology for sizing a hybrid energy system (photovoltaic/wind/battery), using tools that guarantee a minimum cost and high reliability. Hourly data of load, solar radiation, wind speed, and parameters regarding photovoltaic panels, wind generators and batteries, obtained from a small rural property located in the south of Brazil, are used in the sizing methodology. The stochastic values of the solar and wind power generated every hour can be calculated using a statistical model based on Beta and Weibull probability density functions, respectively.

The real contribution of this work is to obtain an optimal combination between the available energy resources and the loads that will be used throughout the year, attending, at the same time, to the minimum cost of the devices and the desired level of reliability, calculated by the LPSP for a period of consecutive hours (critical period). This period may vary from 24 h to 8760 h (from one day to one year) and is determined by the user. The choice of the LPSP value and the critical period will allow the sizing of the system to be realized without an energy deficit concentration through the year. For example, if the user establishes a LPSP of 5% for a period of 168 h (one week), it means that, throughout the year, there will be no period of 168 consecutive hours with an energy deficit longer than 5%. So, there will be a more uniform distribution of energy deficits through the year. On the other hand, if the LPSP is considered for a period of 8760 h (one year), a longer concentration of energy deficits (longer periods with no power supply) may occur, depending on the load demand and the energy resources available. In particular, if the value of the LPSP adopted is 0%, the sizing of the system will not be influenced by the critical period (there will be no deficit energy to be distributed throughout the year).

2. Model formulation

The model formulation is subdivided into three sections: (Section 2.1) solar power, where the parameters to treat solar radiation are referenced; (Section 2.2) wind power, where the parameters to treat wind speed are referenced; and (Section 2.3) sizing methodology, where the simulation process, cost analysis, and optimization model are presented and discussed.

2.1. Solar power

The mathematical model used to calculate the hourly power generation of a photovoltaic panel, $P(S)$, is presented in [8,26] as a function of the available solar radiation data (S) and the technical parameters supplied by the panel manufacturer.

The solar radiation data can be obtained through direct measurements, using solarimetric stations, or using mathematical models, with derived values of other existing meteorological data. Complex models have been developed to represent solar radiation, as spectral models, cloud cover models, probabilistic models, etc. Although some of them are quite complete, the use of a simple statistical model based on probability distribution has turned out good results [8,27].

This work uses a similar procedure with hourly solar radiation data obtained from southern Brazil, using direct measurements. For every hour of a typical day in a month, the average and the variance of the solar radiation are calculated and the probability density function, $f(S)$, which fits the data best, is adjusted. The Beta density function, with bimodal nature, has presented quite satisfactory results for these data [8,28].

The average output power of the photovoltaic module ($P_{\mathrm{S\ med}}$) is the power output in each radiation level [$P(S)$] multiplied by the probability density function [$f(S)$], integrated for all possible values of the radiation [8,28]. So,

$$P_{\mathrm{S\ med}} = \int P(S)\, f(S)\, \mathrm{d}S \tag{1}$$

By solving the integral of Eq. (1), the average output power of PV module, calculated for each hour of a typical day in the month, is found.

2.2. Wind power

Wind generators produce variable electric power. Initially, as the wind speed increases, the generated power also increases up to a certain value, after which the produced power becomes practically constant (nominal power) [29]. When the wind speed reaches the maximum security value, the generation system is disconnected.

A quadratic equation is used to model the generated wind power, $P(v)$, as a function of the wind speed (v) and the technical parameters of the equipment [30].

It is usually accepted that the wind speed can be represented by a Weibull distribution, expressed in terms of two parameters [8,28,31], which can be calculated using the average and the variance of the wind speed dataset.

The average power output of the wind turbine (P_{Vmed}) is the power produced by each wind speed [$P(v)$] multiplied by the probability density function [$f(v)$], integrated for all possible wind speeds [8,28]. So,

$$P_{\mathrm{V\ med}} = \int P(v) f(v)\, \mathrm{d}v \tag{2}$$

By solving the integral of the Eq. (2), the average power output of the wind turbine, calculated for each hour of a typical day in the month, is found.

2.3. Sizing methodology

The developed sizing model minimizes the total cost of the energy conversion equipment (photovoltaic panels, wind generators, and batteries), taking into account the desired reliability of the system. This reliability is represented by the maximum loss of power supply probability (LPSPmax) desired for the project [7,8]. A LPSP value equal to zero means that the consumer demand will always be satisfied, whereas a value equal to one means that it will never be satisfied. The consumer demand will not be satisfied when the energy generated by the photovoltaic panel and wind generator, added to the energy stored in the battery, is not enough to supply the load. The energy will be stored in the battery when the generated production exceeds the load. When the generation is insufficient, the remaining necessary energy will be taken from the battery storage. LPSP represents the probability of the battery energy storage is shorter than an allowed minimum. In a similar way, it can also be expressed as being the accumulated number of hours per year when load is not supplied.

2.3.1. Calculation of LPSP

To calculate the LPSP, two cases can be considered to express energy stored in the battery during the time t [8]:

I. If the energy generated exceeds the energy demanded by the load, the battery charges. So

$$E_{\mathrm{B}}(t) = E_{\mathrm{B}}(t-1) + \left(E_{\mathrm{G}}(t) - \frac{E_{\mathrm{L}}(t)}{\eta_{\mathrm{inv}}} \right) \tag{3}$$

where $E_{\mathrm{B}}(t)$ is the energy stored in the battery during the time t, kWh; $E_{\mathrm{B}}(t-1)$ is the energy stored in the battery during the time $t-1$, kWh; $E_{\mathrm{G}}(t)$ is the energy generated during the time t, by the photovoltaic panel and wind turbine, kWh; $E_{\mathrm{L}}(t)$ is the energy demanded by the load during the time t, kWh; η_{inv} is the efficiency of DC–AC inverter when the load works on an AC line.

II. If the energy demanded by the load is greater than the available energy generated, the battery will be discharged in the amount necessary to meet the load. So

$$E_{\mathrm{B}}(t) = E_{\mathrm{B}}(t-1) - \left(\frac{E_{\mathrm{L}}(t)}{\eta_{\mathrm{inv}}} - E_{\mathrm{G}}(t) \right). \tag{4}$$

The energy stored in the battery during the time t is subject to the following restriction:

$$E_{\mathrm{Bmin}} \le E_{\mathrm{B}}(t) \le E_{\mathrm{Bmax}} \tag{5}$$

where E_{Bmin} and E_{Bmax} are, respectively, the minimum and maximum levels of energy allowed in the battery, kWh. This procedure protects the battery from damage.

When the available energy generated and stored in the battery is insufficient to meet the energy demanded by the load, the deficit called "loss of power supply" (LPS) can be expressed as

$$\mathrm{LPS}(t) = E_{\mathrm{L}}(t) - (E_{\mathrm{G}}(t) + E_{\mathrm{B}}(t-1) - E_{\mathrm{Bmin}})\eta_{\mathrm{inv}} \tag{6}$$

The Loss of Power Supply Probability (LPSP), considered for a period of time T, is the ratio of all values of LPS(t), for that period, and the sum of the energy demanded by the load, and can be expressed as

$$\mathrm{LPSP} = \frac{\sum_{t=1}^{T} \mathrm{LPS}(t)}{\sum_{t=1}^{T} E_{\mathrm{L}}(t)} \tag{7}$$

2.3.2. Procedure for the energy system optimal sizing

An iterative procedure to calculate the optimal sizing of the energy system was developed in MATLAB 2012, and a flowchart is presented in Fig. 1.

The procedure is presented in the following steps:

I. Read hourly data of load, solar radiation, and wind speed, as well as the energy conversion equipment parameters and economic parameters that will be used in the methodology.
II. Calculate, for every hour of the year, the solar and wind average power generated by the energy conversion devices, according to Sections 2.1 and 2.2.
III. Calculate the present worth and costs of the equipment, using their initial costs, maintenance costs, rated powers, annual interest rate, and lifetime [12,14,32]. As the lifetime of the batteries is shorter than the energy-generation devices, new batteries must be purchased along the lifetime of the energy-generation devices.

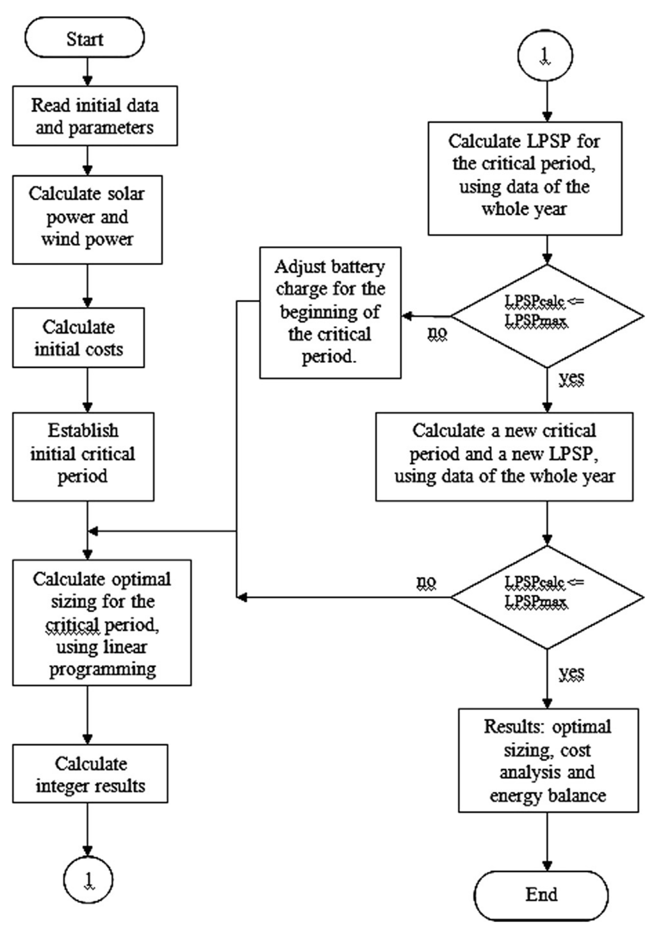

Fig. 1. Flowchart for the energy system optimal sizing.

IV. Establish the initial critical period for the procedure, considered as being a predetermined number of consecutive hours where the longest loss of power supply occurs, using a preliminary comparison between the available load data and the calculated values of solar and wind power.
V. Calculate the optimal sizing of the system (number of photovoltaic panels, wind generators, and batteries) for the established critical period. The optimization model uses linear programming to minimize the system cost and to comply with the desired LPSP, as presented in Section 2.3.3. The algorithm used to solve the linear programming is based on a primal-dual interior point method.
VI. Adjust the results for integer values, using the bifurcation and limit algorithm [33].
VII. Calculate the LPSP for the critical period, according to the methodology presented in Section 2.3.1, using the results obtained in step VI and all available data of load and energy generation. If $LPSP_{CALC} \leq LPSP_{MAX}$, go to step IX. Otherwise, go to step VIII.
VIII. Adjust the level of battery charge, defined for the beginning of the critical period. The parameter used to represent the battery charge level can vary from 1 (initial value for completely charged batteries) to zero (completely discharged batteries), at intervals of 0.01. This adjustment is necessary because the optimal sizing of the system is carried out for the critical period, and the batteries are considered as being charged in the beginning of that period. As this fact may not be true, it is important that the initial level of the battery charge decreases progressively, so that the equipment sizing and the calculated LPSP can also be adjusted, increasing the first and decreasing the second, until the calculated LPSP becomes satisfactory ($LPSP_{CALC} \leq LPSP_{MAX}$). With the adjustment settled, return to step V.
IX. Calculate the new critical period, comparing deficits of energy for all periods of the year, using the results obtained in steps V, VI and VII. With this new period, calculate LPSP again. If $LPSP_{CALC} \leq LPSP_{MAX}$, go to step X. Otherwise, return to step V.
X. Results: optimal sizing and cost analysis.

2.3.3. Optimization model

The optimization model is

$$\text{Minimize } c\,x' \tag{8}$$

$$\text{Subject to} \begin{cases} A\,x' \leq b \\ x \geq 0 \end{cases} \tag{9}$$

The objective function to be minimized consists of the sum of the present worth costs of all energy conversion devices (PV modules, wind turbines and batteries). It is expressed as [34]

$$c_{(1,\,2n+3)} = \left[c_1 c_2 c_3 \quad \text{�} \quad 0 \cdots 0^{2n}\right] \tag{10}$$

$$x_{(1,2n+3)} = \left[x_1 x_2 x_3 \text{�} x_4 \cdots x_{n+3}{}^{n} \text{�} x_{n+4} \ldots x_{2n+3}{}^{n}\right] \tag{11}$$

where c_1, c_2 and c_3 are the present worth costs of the PV module, wind turbine, and battery, respectively; x_1, x_2, and x_3 are the quantities of this equipment; n is the number of consecutive hours for which the LPSPmax is considered; x_4–x_{n+3} are the variables that control the LPSPmax, and x_{n+4} to x_{2n+3} are the variables that allow the occurrence of energy surplus.

The constraints are represented by matrices A and b, expressed as follows:

$$A_{(2n+1\ ,\ 2n+3)} = \begin{bmatrix} -AA' & -BB' & -(ka.CC)' & -DD & DD \\ AA' & BB' & (ka.CC-CC)' & DD & -DD \\ & & KK & & \end{bmatrix} \tag{12}$$

$$b_{(2n+1\ ,\ 1)} = \begin{bmatrix} -\mathrm{LL}' \\ \mathrm{LL}' \\ \mathrm{LPSPmax} \sum_{i=1}^{n} \mathrm{Lh}_i \end{bmatrix} \tag{13}$$

where

$$\mathrm{AA}_{(1,n)} = \left[\mathrm{Eh1}_1 \sum_{i=1}^{2} \mathrm{Eh1}_i \sum_{i=1}^{3} \mathrm{Eh1}_i \cdots \sum_{i=1}^{n} \mathrm{Eh1}_i\right] \tag{14}$$

$$\mathrm{BB}_{(1,n)} = \left[\mathrm{Eh2}_1 \sum_{i=1}^{2} \mathrm{Eh2}_i \sum_{i=1}^{3} \mathrm{Eh2}_i \cdots \sum_{i=1}^{n} \mathrm{Eh2}_i\right] \tag{15}$$

$$\mathrm{CC}_{(1,n)} = \left[\quad \text{�} \quad \mathrm{Eb} \ldots \mathrm{Eb}^{n}\right] \tag{16}$$

$$\mathrm{Eb} = \mathrm{Cbat.\ Ddbat.\ Efbat} \tag{17}$$

$$\mathrm{DD}_{(n,\ n)} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & \cdots & 0 \\ \vdots & & \ddots & & \vdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \tag{18}$$

$$\mathrm{LL}_{(1,\ n)} = \frac{\left[\mathrm{Lh}_1 \sum_{i=1}^{2} \mathrm{Lh}_i \sum_{i=1}^{3} \mathrm{Lh}_i \cdots \sum_{i=1}^{n} \mathrm{Lh}_i\right]}{\mathrm{Efinv}} \tag{19}$$

$$\mathrm{KK}_{(1,2n+3)} = \left[0\,0\,0 \quad \text{�} \quad 1 \ldots 1^{n} \quad \text{�} \quad 0 \ldots 0^{n}\right] \tag{20}$$

where ka is the value concerning the battery charge level (it may vary from 1 to 0); Lh is the hourly energy consumption (kWh); Eh1 and Eh2 are the generated hourly energy for the PV module and wind turbine, respectively (kWh); Ddbat is the discharge depth of the battery; Efbat is the battery round-trip efficiency, and Efinv is the inverter efficiency.

Observing matrices A and b, the existence of three constraints for the optimization model can be verified. The first constraint establishes that the process of discharging batteries, which occurs when the demanded energy exceeds the generated energy, should be limited to the maximum battery discharge depth. This procedure protects batteries against damages and drastic decrease of their lifetime. If this limit is reached, and the demanded energy goes on exceeding the generated energy, an energy deficit will occur. The second constraint establishes that the process of charging the batteries, which occurs when the generated energy exceeds the demanded energy, should be limited by the maximum level of energy supported by the battery. In this case, a surplus production of energy, which will not be stored, may occur. An electronic charge controller must be used to control the battery charge limits. The surplus energy production can be dissipated through resistors and used to heat water. The third constraint establishes the maximum deficit of energy allowed, quantified by the LPSPmax. Therefore, both deficit and surplus of energy may occur, due to the matrix DD. The deficit is controlled by the LPSPmax, which represents the reliability of the system, and the excess is adjusted by the objective function, which guarantees a system with minimum cost.

3. Numerical example

The developed procedure is used to calculate the optimal size of a solar–wind hybrid energy system, for a small rural property located in southern Brazil, with an hourly load varying from zero to 3 kW through the year. Long-term data (20 years) of solar radiation and wind speed recorded for every hour of the day are used to calculate the generated energy. The parameters regarding the equipment of energy conversion, as well as economic parameters, are presented in this section.

I. Photovoltaic panel:
Manufacturer and model: Solartec KS50; nominal power: 0.050 kW; voltage at maximum power: 17.4 V; open circuit voltage: 21.7 V; current at maximum power: 2.87 A; short circuit current: 3.13 A; serial resistance of the equivalent electric circuit: 0.0002 Ω; current coefficient at reference radiation: 0.0016 A/°C; voltage coefficient at reference radiation: 0.144 V/°C; initial cost: R$ 10,000/kW; maintenance cost: R$ 0.01/kWh; and lifetime: 20 years.

II. Wind turbine:
Manufacturer and model: GreatWatt S600; nominal power: 0.600 kW; generation voltage: 24 V; minimum wind speed for energy generation: 3.0 m/s; nominal wind speed after which the generation is constant: 12.5 m/s; maximum wind speed for energy generation: 25 m/s; initial cost: R$ 8500/kW; maintenance cost: R$ 0.024/kWh; and lifetime: 20 years.

III. Battery:
Manufacturer and model: MaxxiEco 100; energy storage capacity (Cbat): 1.2 kWh (100 Ah, 12 V); discharge depth (Ddbat): 0.5; round-trip efficiency (Efbat): 0.85; initial cost: R$ 300/kWh; and lifetime: 4 years.

IV. Other parameters:
Inverter efficiency (Efinv): 0.9; annual interest rate (ia): 10%; period of economic analysis: 20 years.

4. Results and discussion

The optimal sizing of the system is calculated considering six possible scenarios, and the results are presented in Tables 1 and 2. Scenarios 1, 2 and 3 (Table 1) are characterized by three different lengths of critical periods with consecutive hours (periods of 24, 168, and 720 h, representing, respectively, 1 day, 1 week, and 1 month) used for the optimal sizing of the system, considering a LPSPmax of 20%. Scenarios 4, 5 and 6 (Table 2) are characterized by three different maximum LPSP allowed for the project (LPSPmax of 0%, 10% and 30%), considering a critical period length of 168 h.

In Table 1, Scenario 1 presents a more robust sizing of the system (more generated energy and higher costs) with a lower annual deficit of energy, when compared with other scenarios. It happens because Scenario 1 uses a shorter critical period length, for which the LPSPmax must be respected. That is, for any period of 24 consecutive hours along the year, only 20% of the load can be unattended. In fact, most of the periods will present an energy

Table 1
Results of the system optimal sizing for scenarios 1, 2, and 3 (period length of 24, 168, and 720 h), considering an LPSPmax of 20% (for the critical period).

	Scenario 1 ($n=24$ h)	Scenario 2 ($n=168$ h)	Scenario 3 ($n=720$ h)
Number of PV modules	2	10	8
Number of wind turbines	4	3	3
Number of batteries	6	5	5
Generated energy (kWh/year)	3281.51	3008.71	2880.40
Useful energy (kWh/year)	3128.27	2887.74	2807.23
Surplus energy (kWh/year)	153.23	120.97	73.16
Deficit of energy (kWh/year)	160.78	401.32	481.82
Total load (kWh/year)	3289.06	3289.06	3289.06
LPSP for the critical period (%)	20.0	20.0	20.0
LPSP for an annual period (%)	4.9	12.2	14.6
Total cost of the project (R$)	27,855.98	25,672.01	24,661.05
Energy cost (R$/kWh)	1.046	1.044	1.032

Table 2
Results of the system optimal sizing for scenarios 4, 5, and 6 (LPSPmax of 0%, 10%, and 30%), considering a critical period length of 168 h.

	Scenario 4 (LPSPmax=0%)	Scenario 5 (LPSPmax=10%)	Scenario 6 (LPSPmax=30%)
Number of PV modules	7	0	3
Number of wind turbines	4	4	3
Number of batteries	10	7	4
Generated energy (kWh/year)	3602.48	3153.71	2558.04
Useful energy (kWh/year)	3289.06	3118.59	2485.09
Surplus energy (kWh/year)	313.43	35.12	72.95
Deficit of energy (kWh/year)	0	170.47	803.96
Total load (kWh/year)	3289.06	3289.06	3289.06
LPSP for the critical period (%)	0	10.0	30.0
LPSP for an annual period (%)	0	5.2	24.4
Total cost of the project ($)	34,250.90	27,811.90	21,166.76
Energy cost ($/kWh)	1.223	1.048	1.000

Table 3
Cost evaluation for Scenario 2.

Year	IC	MC	TC	PWF	TCP	TCA	EC
0	22,100.00	0.00	22,100.00	1.000	22,100.00	0.00	0.00
1	0.00	63.15	63.15	0.909	57.41	3015.42	2887.74
2	0.00	63.15	63.15	0.826	52.19	3015.42	2887.74
3	0.00	63.15	63.15	0.751	47.44	3015.42	2887.74
4	1800.00	63.15	1863.15	0.683	1272.55	3015.42	2887.74
5	0.00	63.15	63.15	0.621	39.21	3015.42	2887.74
6	0.00	63.15	63.15	0.564	35.64	3015.42	2887.74
7	0.00	63.15	63.15	0.513	32.40	3015.42	2887.74
8	1800.00	63.15	1863.15	0.467	869.17	3015.42	2887.74
9	0.00	63.15	63.15	0.424	26.78	3015.42	2887.74
10	0.00	63.15	63.15	0.386	24.35	3015.42	2887.74
11	0.00	63.15	63.15	0.350	22.13	3015.42	2887.74
12	1800.00	63.15	1863.15	0.319	593.66	3015.42	2887.74
13	0.00	63.15	63.15	0.290	18.29	3015.42	2887.74
14	0.00	63.15	63.15	0.263	16.63	3015.42	2887.74
15	0.00	63.15	63.15	0.239	15.12	3015.42	2887.74
16	1800.00	63.15	1863.15	0.218	405.47	3015.42	2887.74
17	0.00	63.15	63.15	0.198	12.49	3015.42	2887.74
18	0.00	63.15	63.15	0.180	11.36	3015.42	2887.74
19	0.00	63.15	63.15	0.164	10.32	3015.42	2887.74
20	0.00	63.15	63.15	0.149	9.39	3015.42	2887.74
Total	25,672.01						
Energy cost (R$/kWh):			1.044				

deficit of less than 20%, and only the critical period will present a deficit equal to 20%. As the period length increases (scenarios 2 and 3, with periods of 168 and 720 h, respectively), the energy deficit tends to become more concentrated in some hours of the year, permitting a less robust sizing of the system. Maybe, this deficit could be too concentrated in some hours of the year, which may not be interesting for the end consumer.

In Table 2, as expected, the more the LPSPmax increases, the more the energy deficit will be. Consequently, the project will become less robust, with lower costs and lower energy production. As can be seen, the energy cost for 0% of LPSP is equal to R$ 1.223 per kWh of the generated energy, during the lifetime of the project (considered as 20 years). On the other hand, the energy cost for 30% of LPSP is equal to R$ 1.000 per kWh. As the software sizes the system to supply the load with minimum cost (considering the maximum LPSP allowed), the results always show the best combination of the PV panel, wind turbines, and batteries for that condition.

Table 3 presents a cost evaluation for Scenario 2, considering a period of 20 years. In this table, IC is the initial cost of the equipment, including the purchase of new batteries during the considered period (R$/year), MC is the annual cost of the system operation and maintenance (R$/year), TC is the annual total cost of the system, obtained by the sum of the two previous columns (R

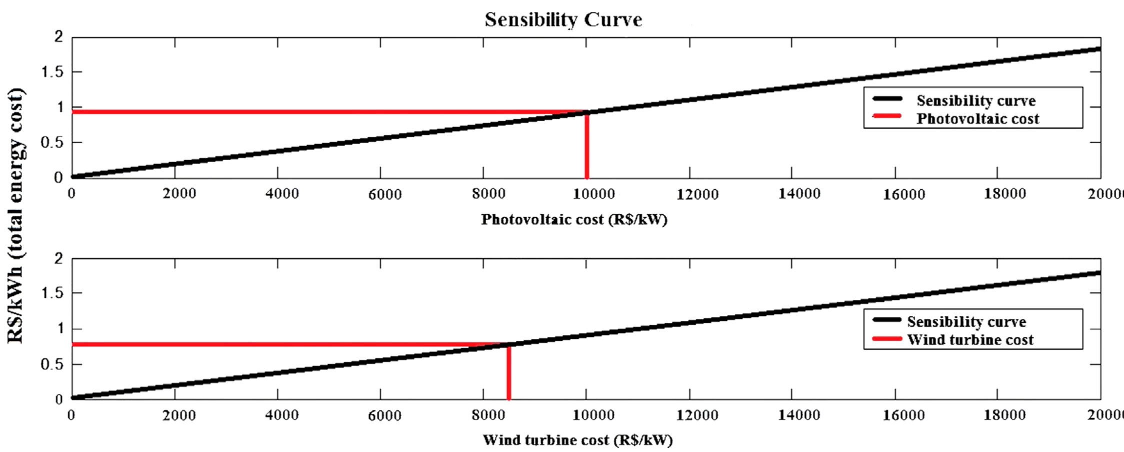

Fig. 2. Sensibility curve for photovoltaic and wind-generation system (Scenario 2).

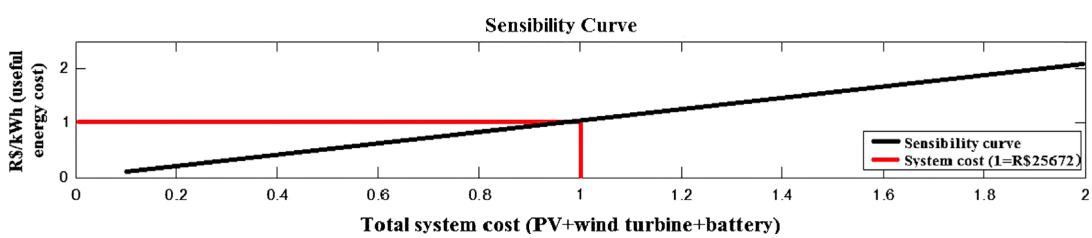

Fig. 3. Sensitivity curve for the energy-generation system (Scenario 2).

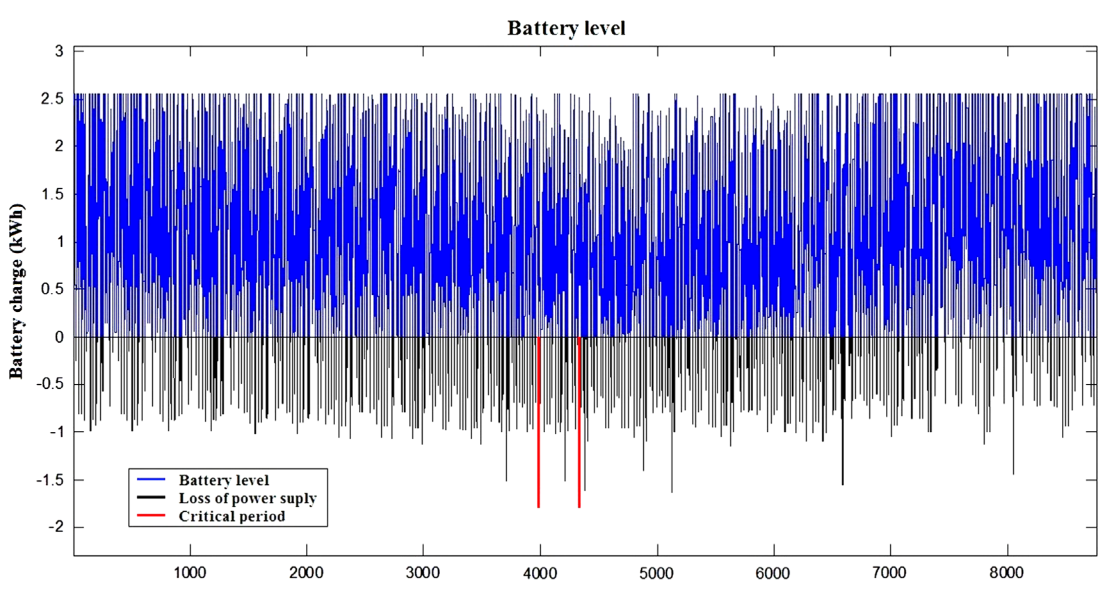

Fig. 4. Level of battery charge through the year (Scenario 2).

\$/year), PWF is the present worth factor for each year, used to compute discounted annual costs (adimensional) [32], TCP is the annual total cost converted to a present value (R\$/year), obtained by the product of the two previous columns, TCA is the total cost annualized (R\$/year), obtained by the multiplication of the total amount of TCP (the sum presented at the end of column 6) by the compound interest factor [32], and EC is the annual useful energy consumption (kWh/year). The ratio of TCA and EC values (except for year zero) gives the energy cost (R\$/kWh), calculated for the system. This value can be used to compare all economically different scenarios.

A sensibility curve for photovoltaic and wind generation systems, for Scenario 2, is presented in Fig. 2. In this figure, the cost of energy (R\$/kWh) is calculated using the equipment initial cost, the maintenance cost, the lifetime, the load factor, and the annual discount rate [8]. The cost of energy, calculated for the photovoltaic system, is R\$ 0.922/kWh and for the wind system is R \$ 0.785/kWh, showing that the latter has a better economic feasibility.

Fig. 3 shows a sensitivity curve, for Scenario 2, indicating the variation that occurs with the useful energy cost (R\$/kWh), in function of the total cost of the system (considering photovoltaic panels, wind turbines, and batteries). The number '1' on the x-axis represents the amount of R\$ 25672.01 (total cost of the system converted to a present value), which is equivalent to a useful energy cost of R\$ 1.044/kWh, showed on the y-axis. If the total cost of the system increases or decreases, along the x-axis, it is easy to obtain the new useful energy cost, along the y-axis.

The battery charge level for the whole year, considering Scenario 2, is presented in Fig. 4. The zero battery charge, located on the y-axis, represents the maximum discharge depth allowed for the battery. A charge level below that line indicates that no more energy is being supplied for the system (occurrence of energy deficit).

5. Conclusions

The developed model for sizing a hybrid energy system presents a methodology based on simulation tools and linear programming. The methodology always results in a minimum cost system and uses the concept of Loss of Power Supply Probability to establish the reliability of the system, which is applied for a critical period of a predetermined amount of consecutive hours, throughout the year.

Some examples to calculate the optimal sizing of the system are presented, varying the number of consecutive hours and the values of LPSPmax desired for the project. By increasing these parameters (period length and LPSPmax), an increase of the energy deficit will occur, resulting in less robust sizing.

The presented results are quite detailed and include, besides the simulation and the sizing of the system, the total values of the generated, useful, surplus and deficit of annual energy. It also presents a cost analysis, of several years, and the system behavior on an hourly basis.

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